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Seismic Determination of Geological Discontinuities
Ahead of Rapid Excavation

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TABLE OF CONTENTS

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13. ABSTRACT

The need for the on-site knowledge of large geological discontinuities ahead of rapid excavation is very desirable for avoiding hazardous or difficult formations ahead of excavation surfaces and for expediting the rate of excavation. Such information could result in fewer machine breakdowns, proper preparation for entry into zones where special precautions must be taken, and considerable savings in cost and human resources.

The objective of this program is to study the feasibility of using ultrasonic acoustic signals and seismic impulses to rapidly predict the presence of large geological discontinuities or other potential sources of danger, such as old mine workings filled with water or gas, lying within a reasonable working range (a few feet to a few tens-of-feet) ahead of excavation surfaces. The principal geologic medium of interest is "hard" or crystalline rock.

The desired goal of this program is to recommend one or more practical ultrasonic systems which could delineate the nearest significant discontinuity ahead of excavation.

This report describes the research and development effort of the first six months of this contract. Section 3 reviews the sonic properties of rocks. In Section 4, ultrasonic detection candidate techniques are analyzed. System design consideration are discussed in Section 5 while experimental results are presented in Section 6.

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SECTION 1

TECHNICAL REPORT SUMMARY

The purpose of this program is to determine the feasibility of using ultrasonic acoustic signals and seismic impulses to rapidly predict the presence of large geological discontinuities or other potential sources of danger, such as old mine workings filled with water or gas lying within a reasonable working range (a few feet to a few tens-of-feet) ahead of excavation surface. The principal geological medium of interest is "hard" or crystalline rock.

A review of existing literature and experimental data was made to determine the characteristics of hard or crystalline rocks, and other materials (that are most likely to be found near geological discontinuities of interest). This review indicates that, at the ultrasonic frequencies of interest, the energy of propagating sound waves in rock is attenuated predominantly by frictional losses. These frictional losses in rock increase very rapidly both with the frequency and the total distance traveled by the sound waves.

A study was made to investigate the feasibility of several non-destructive ultrasonic techniques that could be applied to the detection of the presence of a large geological discontinuity interface. The different techniques analyzed were:

- Resonance
- Continuous waves
- Scattering
- Pulse-reflection

The pulse-reflection (also called pulse-echo) method was found to be the most suited to the proposed application.

We are currently analyzing various configuration of transmitting and receiving transducers which would be needed in a pulse-echo technique to delineate a discontinuity interface that may be inclined to the excavation surface. The simplest and most economical configuration is the combination of a single transmitting source in the center of the excavation surface and three symmetrically located identical receivers. The final selection of one or more promising transmitter receiver configurations will be made after complete analysis of the experimental results of field tests to be conducted in the near future in the Colorado School of Mines' experimental (hard rock) mine. Limited experimental tests will be carried out at this mine to obtain reflection data from known structures of reasonable size.

In order to couple sound energy into and out of rough surface rocks, an intermediary fluid acoustic medium (coupling medium) is needed to fill in spaces between the transducer and the rough surface of the rock. Theoretical and experimental studies were conducted to evaluate various coupling media that are compatible with the environment. Experimental results indicate that water, silicone oil, and glycerine have equal value as couplants; however, such considerations as cost and electrical hazards lead us to suggest the use of glycerine as a contained coupling medium. In applications where the rock surface is very rough and direct contact between transducer housing and the rock surface does not provide adequate acoustic coupling, a noncontacting method of coupling may be used. This could be accomplished by maintaining a water jet (mixed with a wetting agent) between the transducer and rock surface.

A trade-off system study was also undertaken to determine the optimum radiation frequency (or range of frequencies) most likely to delineate geological discontinuities within a given working range ahead of the excavation surface. The results of this theoretical study indicate that in a lossy rock medium, a moderate power pulse-echo detection system operating at about 30-40 kHz can detect large geological discontinuities within one to six meters away from the excavation surface. In low-loss rocks, the maximum distances up to which a discontinuity can be seen is increased. Such a system would have a depth resolution of about 7-10 centimeters.

Based on these theoretical predictions, we are detailing plans for a future field test which will be carried out in the Colorado School of Mines' experimental (hard rock) mine. The results of this test will be used to evaluate the validity of the theoretical predictions of the chosen ultrasonic detection approach and will guide us in the selection and recommendation of a practical ultrasonic system suited to the proposed application.

SECTION 2

INTRODUCTION

The need for the on-site knowledge of large geological discontinuities ahead of rapid excavation is very desirable for avoiding hazardous or difficult formations ahead of excavation surfaces and for expediting the rate of excavation. Such information could result in fewer machine breakdowns, proper preparation for entry into zones where special precautions must be taken, and considerable savings in cost and human resources.

The objective of this program is to study the feasibility of using ultrasonic acoustic signals and seismic impulses to rapidly predict the presence of large geological discontinuities or other potential sources of danger, such as old mine workings filled with water or gas, lying within a reasonable working range (a few feet to a few tens-of-feet) ahead of excavation surfaces. The principal geologic medium of interest is "hard" or crystalline rock.

The desired goal of this program is to recommend one or more practical ultrasonic systems which could delineate the nearest significant discontinuity ahead of excavation.

This report describes the research and development effort of the first six months of this contract. Section 3 reviews the sonic properties of rocks. In Section 4, ultrasonic detection candidate techniques are analyzed. System design considerations are discussed in Section 5 while experimental results are presented in Section 6.

SECTION 3

SONIC PROPERTIES OF "HARD" OR CRYSTALLINE ROCKS

A survey of existing literature on the characteristics of "hard" or crystalline rocks and other materials (that are most likely to be found near geological discontinuities of interest) resulted in the following observations.[1,2]

(1) Sound velocity in hard rocks depends on a large number of factors such as mineralogical composition, fluid content, temperature, pressure, grain size, cementation, direction with respect to bedding and foilation, and alteration. For these reasons, velocity data from the literature provide known ranges, and if possible, a statement of average values or typical ranges. The range of sound velocity of longitudinal waves in hard rocks is cited to be 4000-6500 meters/second.

(2) Because of porosity in rocks, the density of a hard rock varies from sample to sample over a range from 2500 to 3.400 kg/m^3.

(3) A number of loss mechanisms have been suggested to explain the dissipation of acoustic energy in a vibrating solid.

These can be grouped into four main types: (a) thermal losses, (b) ferromagnetic losses, (c) scattering losses, and (d) frictional losses. The losses due to the first two mechanisms are relatively minor. Scattering losses become significant only when the sound wavelengths approach the grain size in coarsely crystalline rocks. The grains will have varied orientations causing an impedance mismatch between adjacent grains and resulting in scattering of sound energy. For grain diameter smaller than a wavelength, the scattering losses are found to show a dependence on the third power of the grain diameter, and the fourth power of frequency.[3] Thus, scattering losses must be taken into consideration when the grain size is about 1/10 of a wavelength or greater.

Frictional losses result from the sliding or movement of one surface past another within the rock. It is widely acknowledged that this mechanism probably accounts for most of the energy loss by acoustic waves propagating through a solid material. Several mathematical models to account for frictional losses have been developed, but none of these fits the experimental data for all frequency ranges.

System considerations (discussed later) have indicated that the frequencies of interest lie in the range of 10-100 kHz. At these frequencies, the dominant loss mechanism would be frictional losses. The review of literature and experimental data on frictional losses in rocks indicates that these losses are relatively insensitive to temperature changes but are dependent upon pressure, porosity, saturation, grain size, and the type of wave and direction of propagation. The attenuation of signal amplitude due to frictional (and scattering losses if any) is usually described by $\exp(-\alpha L)$ where L is the distance traveled by the sound wave, and α is the attenuation coefficient. The attenuation coefficient α (from only frictional losses) is known to vary linearly with the radiation frequency f. Typical values of α range from $3.0 \times 10^{-6}f$ to $30 \times 10^{-6}f$ sec/m which makes the quality factor Q ($\pi f/\alpha v$ where v is the sound velocity) essentially independent of frequency. The corresponding typical values of Q range between 20-200. Thus, the frictional losses in rocks can attenuate the signal from $26 \times 10^{-6}f$ to $260 \times 10^{-6}f$ decibels per meter of distance traveled by the signal.

In order to establish the feasibility of the proposed ultrasonic detection system for predicting geological discontinuities in "hard" or crystalline rock, we have chosen granite as a typical propagation rock material for both theoretical and experimental investigations. Typical characteristics of granite rock are assumed to be

Average Velocity = 5.5 km/sec

Mean Density = 2.65×10^3 kg/m^3

Attenuation coefficient $\alpha = 3.9 \times 10^{-6}f$ to $27 \times 10^{-6}f$ sec/m

A geological discontinuity of interest is assumed to be formed by the combination of a "hard" or crystalline rock in front of a discontinuity interface and water, gas, or unconsolidated earth materials behind it. The proposed detection system is based upon detecting reflections from such a discontinuity interface. Water or gas behind a discontinuity would reflect echos that are considerably larger than the ones reflected from unconsolidated earth materials located behind a discontinuity.

SECTION 4

ULTRASONIC DETECTION TECHNIQUES

4.1 GENERAL

A geologic discontinuity occurs whenever there is an acoustic impedance between two media. Acoustic impedance Z is given by the product of the density ρ and the sound velocity v in the medium (i.e., $Z = \rho v$). An ultrasonic detection system to detect a discontinuity interface which is at least as large as the excavation surface and which has lateral dimensions larger than the probing signal wavelength has been proposed and is analyzed here.

At the wavelengths of interest, the propagation rock medium of interest appears to be semi-infinite to the waves propagating through it. In such a medium, longitudinal, shear and Rayleigh waves can be excited. Longitudinal and shear waves propagate throughout the medium, whereas Rayleigh waves propagate only over the free interface of a solid medium. In a field problem, a fluid acoustic coupling medium can be used to couple acoustic energy into and out of rocks. Since only longitudinal waves can be excited in fluids, these waves will be used in the detection system. Longitudinal waves travel the fastest of the three wave types, while Rayleigh waves travel the slowest.

Any ultrasonic detection technique, which can nondestructively measure the thickness of a plate (accessible from one side only) can also be used to detect the presence of a geological discontinuity interface in a rock medium. Detection techniques are usually classified according to the measured quantities.[4-6] These are:

- Resonance (standing wave) techniques
- Continuous wave techniques
- Scattering techniques
- Pulse-reflection techniques

4.2 RESONANCE (STANDING WAVE) TECHNIQUES

The resonance technique is a well established method for measuring material thickness, especially that of metals. This technique is applicable when transverse dimensions of the material are large compared to both the probing wavelength and the thickness of the plate. In the usual resonance method, acoustic energy is coupled to a material of unknown thickness, either directly or through a liquid coupling media. A continuous wave (CW) acoustic signal is sent into the material under test; the frequency (and therefore the wavelength) of these waves is varied

manually or automatically until the thickness of the material is an integral multiple of one-half of the signal wavelength. Standing waves are then set up within the material causing it to resonate or vibrate at larger amplitude. Resonance is indicated by its loading effects upon the transducer coupling energy into the medium. The thickness L of the unknown material is given by

$$L = n\ \lambda/2 = \frac{nv}{2f} \tag{1}$$

where λ = wavelength in the material, v = sound velocity in the material, f = fundamental resonance frequency; and n gives the integral number of half-wavelengths set up in the material (which is also the harmonic number of the fundamental resonance frequency).

The thickness resolution of a resonant system is influenced by such factors as (1) the harmonic number n, (2) loss characteristics of the material as well as the coupling medium, (3) the shape and size of the material, and (4) the nature and point of excitation. This method is applicable to problems where both surfaces of the material to be gaged are parallel to each other. In the proposed application, both material surfaces may not always be parallel to each other, and therefore this method is very limited in scope for the present application. Furthermore, the thickness resolution is expected to degrade with increasing thickness because a decreasing amount of signal is reflected back to the incident surface with increasing thickness of a lossy material. Hence, it is not a suitable candidate technique.

4.3 CONTINUOUS WAVE PROPAGATION TECHNIQUES

This method uses continuous waves of constant frequency. The depth of a discontinuity is measured from the transit time which is obtained by comparing the phase of the reflected wave to that of the incident wave. Since the phase difference can be measured between 0 to 2π, this method is limited to a thickness less than a wavelength. Thicknesses greater than a wavelength can be measured, if the approximate thickness is known to within a wavelength in advance. Although low frequencies can be used, this method is limited to very lossy materials because multiple reflections impede the measurement. The limitations of this method make it unsuitable as a candidate technique.

4.4 SCATTERING TECHNIQUES

Acoustic signals propagating in an inhomogeneous rock medium are known to be attenuated both by frictional and scattering loss mechanisms. In applications where signal attenuation is predominantly due to scattering, the return back-scattered signal would be made up of contributions from different scattering sources within the formation. Scattering sources

at progressively greater distances from the surface within the medium are expected to contribute at successively later times. If the scattering characteristics of the medium change with increasing penetration, as they well might if the lithology changes significantly (as when crossing a boundary between hard rock and gouge), the amplitude and possibly the frequency characteristics of the return signal might change. The presence of such an interface could then show up as an anomaly in the noise amplitude or character at a time corresponding to the depth of a discontinuity interface. The scattering loss mechanism becomes significant when the signal wavelength approaches the grain size. The signal attenuation due to scattering losses is usually described by exp $(-\alpha_s L)$ where α_s is the scattering attenuation coefficient and L is the distance traveled by the signal. In a hard crystalline rock medium, consider a grain size of about 1/16 inch. For significant scattering losses, the signal wavelength should be about the same size as the grain size which suggests that the signal frequency should be about 3 MHz. At 3 MHz, the frictional losses alone would attenuate the signal by about 390 db/meter in a typical lossy rock medium having a Q of about 40. This exhorbitant amount of attenuation due to frictional losses alone would limit the application of this system to see discontinuities at no more than 1/5 of a meter away from the excavation surface. Hence, this is not a suitable candidate technique.

4.5 PULSE-REFLECTION TECHNIQUES

Pulse reflection is a well established technique for nondestructively measuring the thickness of a testing material or detecting its internal flaws. The basis of this method is to transmit a burst of acoustic energy into a test material; whenever the transmitted pulse encounters a reflector (i.e., an impedance mismatch interface), an echo is reflected back towards the receiving transducer. The transmit time t of the pulse from the transmitter to the discontinuity and back to the receiver can be used to determine thickness L of a test material or the distance to a flaw by

$$L = \frac{vt}{2} \qquad (2)$$

provided the sound velocity v test material is known. Since, in most applications, the velocity is a known quantity, the thickness accuracy is directly related to the accuracy of reading the arrival time. The largest reading error would correspond to half of the period of the carrier signal. This method is generally limited to thicknesses where the transit time of the echo is greater than the duration of the transmitted pulse. This technique has several advantages over resonance and CW techniques. This method requires lower average power while the peak power is high enough to operate at favorable signal-to-noise ratio; it is also possible to discriminate in the time-domain against (1) unwanted reflections, (2) any undesired types of waves, and (3) direct acoustic and electromagnetic coupling between the transmitter and receiver. This system is relatively easy to implement.

A disadvantage of a pulse-reflection technique, compared to a continuous wave technique, is that the received echo signal is distorted due to the preferential attenuation of higher frequency components of the transmitted pulse by frictional and scattering losses. This results in the spreading of the pulse echo and creation of a low-frequency "tail" even in cases when a single cycle of sound wave is transmitted. Hence, in a highly-lossy rock medium, the resolving power of this system is expected to degrade with increasing depth of the discontinuity interface.

The accuracy with which the thickness of a test material can be measured by the above described system is limited to half of the period of the carrier signal. This accuracy may be improved by using frequency modulated (FM) in place of pulse-modulated (PM) transmitted pulses. In an FM system, the frequency of the transmitted pulse is varied periodically in some fashion. In this case, the distance of a reflector is not identified by the transit-time between the transmitted and received pulses, but by the frequency difference between the received FM pulse and a frequency-modulated local oscillator. The FM system,[7] as compared to a PM system, is known to have higher signal-to-noise ratio but it requires relatively longer duration pulses. The longer duration of pulses results in increased minimum distance at which a closest discontinuity interface can be detected. In some situations, however, an FM system may be superior than a PM system. A PM system is usually less complex than an FM system, and therefore we will try to use a PM system wherever it is practical. In situations where a PM system is inadequate, we will evaluate the use of an FM system.

4.6 SELECTION OF THE MOST PROMISING ULTRASONIC TECHNIQUE

In the proposed application, it is desired to measure the depth of a geological discontinuity in hard rocks which may or may not be lossy. In spite of the fact that the return echo in a pulse-reflection technique will be somewhat distorted, the pulse-modulated techniques, among all others discussed, appear to be most suited to our application.

In the next section, a detailed discussion of the pulse-modulated technique is presented.

4.7 PULSE-MODULATED REFLECTION METHODS

These methods are also called pulse-echo methods. A typical pulse-echo system for measuring the thickness of a test specimen is shown in Figure 4-1.

The burst of acoustic test signal is usually generated by applying either a short pulse-modulated CW electrical signal (PM-CW) or a dc impulse that excites the transducer to ring at its resonant frequencies for several oscillations. The transmitted signal is then reflected back by a discontinuity interface at which impedance mismatch occurs.

At normal incidence, the ratio between reflected energy W_r and incident energy W_i is given by the reflection coefficient

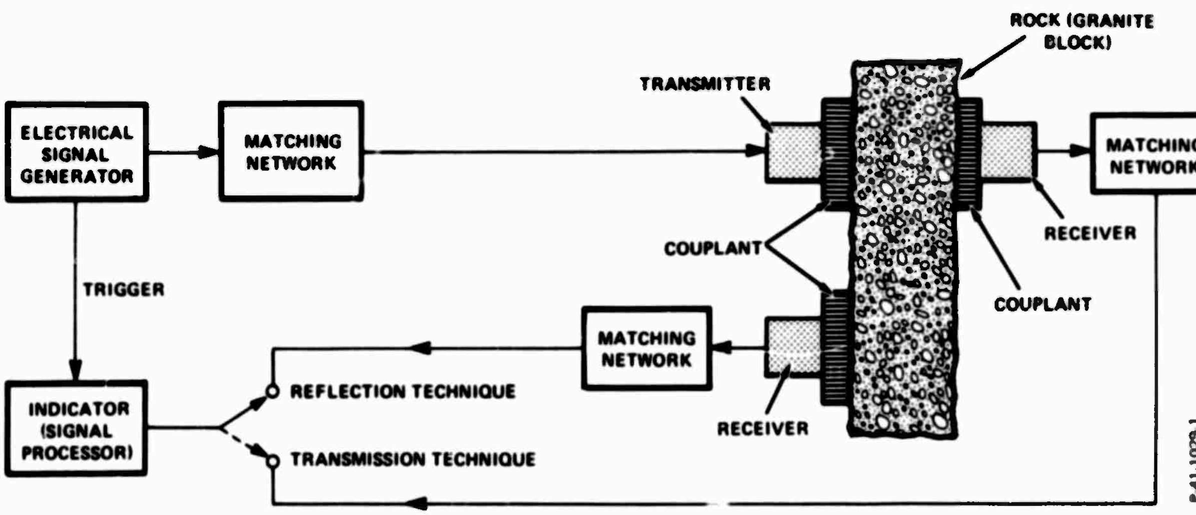

Figure 4-1 - Typical Block Diagram of Pulse-Echo (or Pulse Transmission) Detection System

$$R = \frac{W_r}{W_i} = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1}\right]^2 = \left[\frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}\right]^2 , \qquad (3a)$$

and the transmission coefficient is given by

$$T = (1 - R) = \left[\frac{2 Z_2}{Z_1 + Z_2}\right]^2 = \left[\frac{2 \rho_2 v_2}{\rho_2 v_2 + \rho_1 v_1}\right]^2 \qquad (3b)$$

where ρ, v, and Z, respectively, are the density, sound velocity, and impedance of the medium. The subscripts 1 and 2 refer to the media in front and behind the discontinuity, respectively.

Mode conversion to other types of waves occur when a longitudinal sound beam is incident other than normally to a discontinuity interface between two solid materials with different sound velocities. In this case, energy is carried by reflected and refracted shear sound beams which are generated by mode-conversion. If the incident angle exceeds the critical angle for production of refracted shear waves, refracted shear waves cannot be produced; however, still another waveform, known as Rayleigh waves, can be produced which propagate at the free surface of a solid material.

Transmitter-Receiver Transducer Configurations

For detecting a discontinuity interface parallel to an excavation surface, a minimum of one transmitter and one receiver is needed. They can be arranged in one of the three configurations. These are: (1) a common transmit-receive (TR) probe employing a single transducer with common connections to the transmitter and receiver amplifier unit, (2) separate transmitting and receiving transducers which are acoustically as well as electrically insulated from each other and housed in a single probe, and (3) separate transmitting and receiving transducers mounted in separate probes. If a common TR probe is used, a minimum "dead time" equal to the duration of the transmitted pulse is required before the return signal can be detected. However, when separate transducers are used for transmitting and receiving, consideration must be given to the presence of unwanted waves propagating over the surface on which both transducers are mounted. These can be direct longitudinal and shear waves, and Rayleigh waves, all of which travel with different sound velocities. Hence, a separate receiver must be so located that the return signal arrives either before the arrival or after the departure of these surface waves.

Since the objective of this program is to delineate a geological discontinuity interface which may be inclined to the excavation surface, at least one transmitter and three receivers are needed in a pulse-echo method. The simplest and most economical transducer arrangement would be to use a single transmitting probe in the center of the excavation surface, and three symmetrically located receiving probes.

In addition to this simple arrangement, other transmitter-receiver arrangements have been included in a trade-off study undertaken to select one or more promising transmitter-receiver transducers configurations for our application. The various transducer arrangements considered are:

- Four common transmit-receive (TR) transducer probes
- One transmitting transducer and multiple receiving transducers
- One transmitting transducer and phased-array receiving sonar[8]

This trade-off study is based on such system parameters as: (1) the compatibility of the probe's configuration with the tunneling process, (2) maximum area of excavation surface available for placing transducer probes, (3) average size of rock surface-roughness relative to radiation wavelength, (4) electro-acoustic coupling between transmitter and receiver circuits, (5) relative amplitudes and times of arrival of (a) direct and Rayleigh waves propagating over the excavation surface, and (b) surface waves that may be reflected from the corners formed by the excavation surface and the interior surface of the tunnel, (6) duration of incident pulse relative to the transit time of the echo reflected by a desired discontinuity at the closest distance of interest, (7) measurement time, and (8) ease with which the detection system can be implemented in the field.

Although this trade-off study is not yet completed, it is clear that the receiving transducer arrangement in the form of a phased-array sonar is cumbersome and impractical for this application. A phased-array sonar is useful for steering a narrow beam over a large area. In such applications, a receiving phased-array is usually placed in the far-field region of the reflector and thus allows very simple phase compensation between elements for steering the beam over a given area.

System considerations (discussed later) indicate that the detection system selected for this application is expected to be operating at about 30 - 40 kHz. Here, the far-field region of a reflecting interface begins beyond 300 meters away. The phased-array receiving sonar would therefore be located in the near-field region of the discontinuity interface. Consequently, a very complex system of phase compensation between transducers would be required to steer the beam over a given area.

SECTION 5

SYSTEM DESIGN

In this section, the basic principles underlying the design, development, and testing of a pulse-reflection technique are discussed. The effects of various parameters of the detection system are also analyzed in a system trade-off study.

5.1 GENERATION AND RECEPTION OF ACOUSTIC SIGNALS

The acoustic signal, in general, can be generated by a mechanical source or an electromechanical transducer. A mechanical source (such as a mechanical impactor or explosive charge) is inefficient at the (ultrasonic) frequencies of interest. An electromechanical transducer can be used as either a transmitter or a receiver since it transforms mechanical energy into electrical energy, and vice versa. At ultrasonic frequencies, transducers made out of solid materials that have magnetorestrictive or piezoelectric properties are known to have high electromechanical conversion efficienty. Magnetorestrictive transducers become less efficient than piezoelectric transducers above a frequency of 60 - 100 kHz. In view of these considerations, the properties of piezoelectric materials have been further investigated for the fabrication of both transmitting and receiving transducers.

Of the many materials with piezoelectric properties, quartz and cast ceramic materials (such as lithium sulphate, barium titanate, lead meta-niobate, and lead zirconate-titanate base materials) are commonly used in nondestructive measurements. Except for the fact that quartz is a stronger and lower-loss material, ceramics are more efficient and lower in cost. Furthermore, ceramics can be readily processed into larger or more complex shapes and they require a much lower driving voltage.

Two piezoelectric coefficients, d and g, are important in evaluating transducer material. The constand d measures the amount of charge produced on the electrodes attached to a piezoelectric crystal which is subjected to a given force or the deflection caused by a particular applied voltage. The g constant is used to denote the field produced in a piezoelectric crystal by an applied stress. The constants d and g are interrelated by the dielectric constant $\varepsilon_o \varepsilon_r$ of the material by

$$g = \frac{d}{\varepsilon_r \varepsilon_o} \qquad (4a)$$

where ε_o is the permittivity of vacuum. A piezoelectric material with a large value of d is desirable for a transmitter, while the material

with a large value of g is useful for a receiver. Essentially, d and g should both be high in order to obtain optimum transfer of mechanical energy into electrical energy or vice versa. This is evident from the fact that the electromechanical coefficient k_c^2 is related to g, d and Young's modulus c by the following relationship

$$k_c^2 = gdc = \frac{e^2}{\varepsilon_r \varepsilon_o c} \tag{4b}$$

The physical constants of several transducer materials are listed in Table 5-1.[9] PZT-4 (lead zirconate-titanate base) ceramic appears to be best suited as a transmitter material since it has high power capabilities (due to high resistance to depolarization and low dielectric losses under high electric drive), a high electromechanical coupling coefficient, and a high curie point. Because of low dielectric losses, PZT-4 transducers are not well suited to generate short transient pulses. In applications where relatively short transient response of a transducer is of interest, lead meta-niobate (LMN) may be used since the quality factor of LMN is 1/40 of the value of PZT-4. The transient response of a transducer can be further shortened by matching the acoustic impedance of the transducer with that of the radiation medium.

Lithium sulphate appears to be a most efficient receiver material. However, its usage is limited to temperatures below 75°C because it decomposes at about 110°C. LMN and lead zirconate-titanate (PZT-4 and PZT-5) appear to be the next best materials. Since both PZT-4 and PZT-5 have higher dielectric constants than LMN, the loss in signal strength due to cable loading would be less with a PZT than with an LMN receiver.

Some of the basic principles that are needed in the design and development of a detection system are briefly described in Appendix A.

5.2 EFFECTS OF COUPLING MEDIUM

An intermediary acoustic coupling medium will be required to fill in uneven spaces to provide intimate acoustic coupling from a transducer to a rock surface. A couplant can be almost any material, liquid, semiliquid, which (a) is compatible with the tunneling operations, (b) wets both the rock surface and the face of the transducer probe, excluding air between them, (c) is easily contained, is homogeneous and free from bubbles or solid particles which reflect or scatter the incident beam, (e) is not corrosive, toxic, or flammable, and (f) has an acoustic impedance approaching that of bounding media (this is an ideal rather than a restrictive requirement).

The thickness of a couplant layer would affect the apparent acoustic impedance of a coupling medium if the transit time of the incident pulse through the coupling layer is less than the duration of the incident pulse.

Table 5-1 - Constants of Various Piezoelectric Materials

Physical Property	Quartz 0° X-cut	Lithium Sulfate 0° Y-cut	Barium Titanate Type B	Lead Zirconate-Titanate		Lead Meta-Niobate	Units
				PZT-4*	PZT-5*		
Density ρ	2.65	2.06	5.6	7.6	7.7	5.8	10^3 kg/m^3
Acoustic impedance ρc	15.2	11.2	24	30.0	28.0	16	10^6 kg/m^{2}S
Maximum operating temperature	550	75	70-90	250	290	500	°C
Dielectric constant	4.5	10.3	1,700	1,300	1,700	225	---
Electromechanical coupling factor for thickness mode k_{33}	0.1	0.35	0.48	0.64	0.675	0.42	---
Electromechanical coupling factor for radial mode k_p	0.1	---	0.33	0.58	0.60	0.07	---
Elastic quality factor Q	10^6	---	400	500	75	11	---
Piezoelectric modulus for thickness mode d_{33}	2.3	16	149	285	374	85	10^{-12} m/V
Piezoelectric pressure constant g_{33}	58	175	14.0	26.1	24.8	42.5	10^{-3} V/m/(N/m^2)
Volume resistivity at 25°C	$>10^{12}$	---	$>10^{11}$	$>10^{12}$	$>10^{13}$	10^9	---
Curie temperature	575	---	115	320	365	550	°C
Young's modulus E	8.0	---	11.8	8.15	6.75	2.9	10^{10} N/m^2
Rated dynamic tensile strength	---	---	---	3,500	4,000	---	psi

*PZT - It is a trademark of the Clevite Corporation.

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This is usually the case in most pulse-reflection applications. If the duration of incident signal pulse is short compared to the transit time through the couplant (i.e., signal pulse cannot "bite its own tail" after a single reflection in a couplant), a given incident pulse splits into reflected and transmitted series of completely separated and mutually independent pulses. The relative amplitude of these pulses can be calculated according to equation (3) if it is repeatedly applied to the individual reflection and transmission phenomena. As a result of repeated splitting, the amplitude of transmitted pulse sequence then decreases continuously, but remains completely independent of the thickness of the coupling layer.

For the case when the thickness of a couplant is less than the width of the pulse propagating through it, interference occurs. These interferences are similar to the one experienced by continuous waves. The general expression for the energy transmission coefficient T for a plane sound wave, incident normal to a pair of parallel interfaces, is given by

$$T = \frac{4\,\rho_3 v_3 \rho_1 v_1}{\left(\rho_3 v_3 + \rho_1 v_1\right)^2 \cos^2 k_2 \ell + \left(\rho_2 v_2 + \rho_3 v_3 \rho_1 v_1/\rho_2 v_2\right)^2 \sin^2 k_2 \ell} \tag{5}$$

where ρ and v are, respectively, the density and sound velocity of the media. Subscripts 1, 2, and 3 refer respectively to the transducer, coupling medium, and radiation medium. ℓ is the thickness of the coupling layer, and $k_2 = 2\pi/\lambda_2$ where λ_2 is the sound wavelength in the coupling medium.

If the acoustic impedance of a couplant is intermediate between those of the bounding media, transmission through the couplant is maximum when its thickness is an odd multiple of a quarter wavelength. If, in addition, the acoustic impedance of the couplant is equal to the geometric mean of the impedances of the bounding media, there is complete transmission. If, however, the acoustic impedance of the coupling layer is not intermediate between those of the bounding media, then the transmission is maximum when the thickness of the layer is a multiple of a half wavelength. The transmission in this case becomes minimum when the thickness is an odd multiple of a quarter wavelength. For coupling layer thicknesses smaller than a quarter wavelength, the transmission is less than it would be without the couplant, and the transmission decreases with increasing thickness of the coupling layer.

So far we have assumed that the surface of the radiation medium is smooth, which would not be the case with a rock medium. Hence, a brief discussion is presented on the possible effects of a rough radiation surface.

5.3 SURFACE ROUGHNESS EFFECTS

When acoustic energy travels from a transducer to rock, or vice-versa, via a coupling medium, the surface roughness of the rock can contribute to loss of acoustic energy due to scattering. When longitudinal plane wavefronts are incident upon a rough surface, they enter at various angles with respect to the normal at various points on the rough surface. When the angle of incidence exceeds the critical angle for a certain mode of propagation within the rock material, these waves are not transmitted, and mode-conversion to shear and surface waves may result. Thus, a portion of the beam is interrupted in transmission across a rough surface rock.

There are certain degrees of surface roughness that can produce phase cancellation in the transmitted wave, even with normal incidence. The sound that travels through a fluid couplant lags the sound which travels through a rock because sound velocity in a coupling fluid is lower than that in a typical rock. The sound recombines inside the rock so as to accommodate the difference in travel time. When this difference in travel time is equal to one-half the period of sound wave, a pressure wave combines with a rare fraction wave, and the resultant energy is nearly zero inside the rock. The average peak-to-valley roughness that causes the destructive interference is known as the critical roughness R_c and is given by[11]

$$R_c = \frac{\lambda_2 \, v_1}{2\,(v_2 - v_1)} = \frac{\lambda_1 \, v_2}{2\,(v_2 - v_1)} \qquad (6)$$

where λ_1, λ_2 are the wavelengths of sound in the couplant and rock, respectively; and v_1 and v_2, respectively, are the velocities of the sound in the couplant and rock. There are similar effects for roughness values of 2 R_c, 3 R_c, etc.

The resolution and sensitivity of a detection system usually decreases when rough surface materials are being investigated. The surface roughness effects are usually insignificant when the peak-to-valley roughness is less than 1/8 of the wavelength in the coupling medium.

5.4 PRELIMINARY SYSTEM DESIGN CONSIDERATIONS

A trade-off study between various system parameters was undertaken to determine the optimum radiation frequency (or range of frequencies) most likely to delineate large geological discontinuities in "hard" or crystalline rock medium.

In this study it was assumed that (1) the discontinuity interface is at least as large as the excavation surface, (2) the transmitter beamwidth is such that it illuminates the discontinuity interface located

within a minimum distance of L_{min} to a maximum distance of L_{max}, from the excavation surface, (3) the signal is attenuated primarily by frictional losses in the rock, (4) the reflected signal is detected by a non-resonant transducer receiver, (5) the separation between transmitter and receivers is small enough so that the total distance traveled by the received signal can be approximated by twice the depth of a discontinuity, and (6) no signal other than reflected longitudinal waves appears at the receiver.

The open-circuit peak voltage V_r across a non-resonant receiver due to an acoustic pulse reflected from a discontinuity at a distance L (from the excavation surface) is related to the peak transmitter excitation voltage V_t by

$$V_r = C_1 \left[\frac{A_t V_p R f}{L v_m \exp(2\alpha L)} \right] \quad (7)$$

where

α = Attenuation coefficient due to frictional losses

R = Reflection coefficient at the discontinuity interface

A_t = Transducer radiating surface area

f = Carrier frequency

v_m = Sound velocity at the radiating face of the transmitter

L = Depth of the discontinuity interface from the excavation surface;

and C_1 is the constant of the system which is a function of rock and coupling media characteristics, and transmitting and receiving transducer properties.

The noise detected in the received signal would be due to contributions from lattice vibrations in the acoustic detector and from conventional noise of the receiving preamplifier.

The acoustic noise intensity I^{ℓ} due to lattice vibrations is given by[12]

$$I^{\ell} = 430 \text{ kT } \Delta f \frac{f^2}{v_r^2}$$

where

k = Boltzman constant

T = Temperature (in Kelvin)

Δf = Band-width of the received signal

v_r = Particle sound velocity in the receiver material

The peak electrical noise voltage $V_r{}^{\ell}$ due to the lattice vibrations can be reduced to

$$V_r{}^{\ell} = C_2 \frac{f}{\sqrt{L_{min}}} \qquad (8)$$

where C_2 is a constant which is a function of receiver and rock properties. For a PZT-5 non-resonant receiver (1/2 cm thick), the noise voltage due to lattice vibrations can be approximated by

$$V_r \approx \frac{1.2 \times 10^{-8} \, f \, (\text{kHz})}{\left[L_{min} \, (\text{meter})\right]^{1/2}} \text{ Volts} \qquad (14)$$

This noise voltage would be about 1/2 of a microvolt at f = 40 kHz for a system designed to detect discontinuities at no closer than 1 meter away from the excavation surface.

Since the noise voltage of a preamplifier is expected to be a fraction of a microvolt, it will be neglected in further calculations.

Figure 5-1 shows the maximum distance up to which a discontinuity can be detected in a granite rock by a PM-CW system. In these results, it is assumed that (1) the system bandwidth is 3 kHz which corresponds to a transmitted signal pulse duration of about 300 microseconds, (2) the transmitter is a half-wavelength-thick sandwich (which has 1/2 cm-thick PZT-4 discs), (3) both transmitter and receiver face diameters are 5 cms, and (4) the minimum reflected signal voltage is at least ten times as large as the noise voltage. These curves are drawn as a function of signal frequency f for two extreme values of the attenuation coefficients: namely, low-loss ($\alpha = 3.9 \times 10^{-6}$ f sec/m, or Q = 125) and high-loss ($\alpha = 27 \times 10^{-6}$ f sec/m, or Q = 20). In a lossy-rock (Q = 20), it is estimated that a moderate power, PM-CW detection system operating at 40 kHz can detect signals reflected from a large geological discontinuity located up to 6 meters away from the excavation surface. In low-loss rocks, the

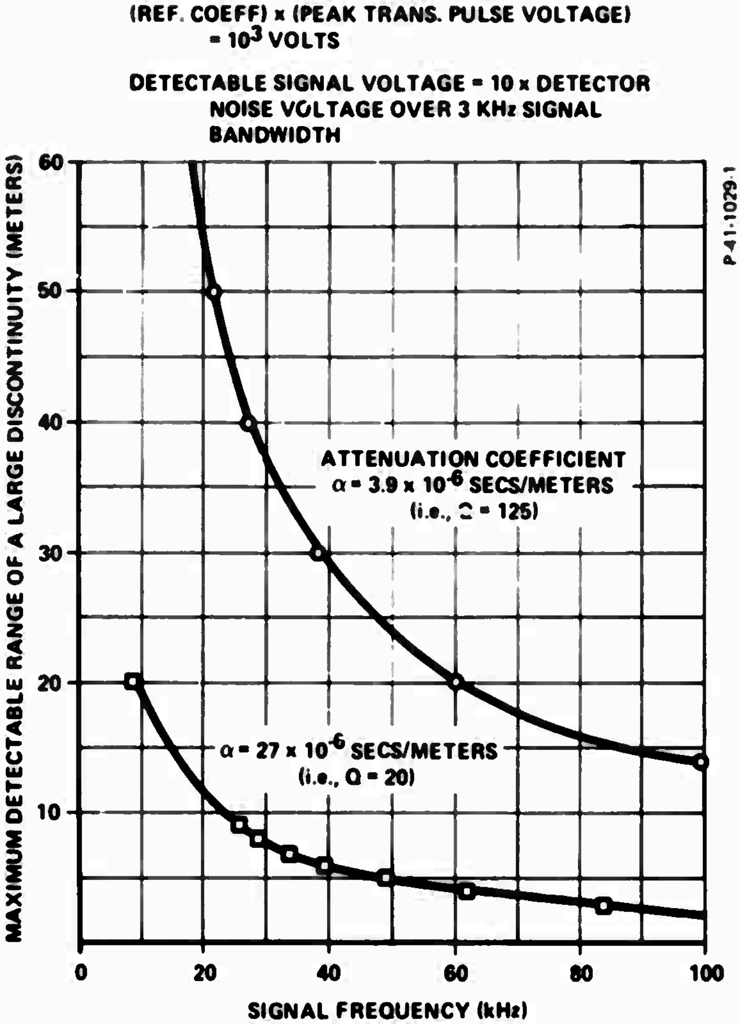


Figure 5-1 - Calculated Range-Frequency Curves for a Pulse-Modulated CW System Operating in Granite Rock

maximum distance up to which a discontinuity can be seen is increased by many times. For example, in low-loss granite (Q = 125), the same discontinuity can be seen up to 29 meters away from the excavation surface. The pulse-repetition-frequency is chosen to be about 5 Hz such that no range ambiguity exists due to reverberations, even in very low-loss rocks. The range resolution of such a system is about half of the signal wavelength, which is 7 cm in granite at 40 kHz.

A PM-CW system operating at about 30 - 40 kHz, capable of detecting large discontinuities up to 6 meters in lossy rocks, appears to be a reasonable detection system for the application under consideration, and hence we will concentrate our future efforts on such a system.

SECTION 6

EXPERIMENTAL INVESTIGATION

In order to establish the validity of the chosen ultrasonic pulse-echo technique, preliminary laboratory and field experiments have been designed to give information on (1) the coupling of acoustic energy into and out of smooth as well as rough surface "hard" or crystalline rocks, and (2) the reflection from known hard rock structures of reasonable size.

6.1 HARD CRYSTALLINE ROCK TEST SPECIMEN

The test frequencies of interest are in the 30 to 40 kHz range, and hence the test wavelength in granite would typically range between 18 to 24 cm. Although it is desirable to have a test specimen whose dimensions are such that it laterally appears as a semi-infinite medium at the test wavelengths, the considerations of availability, handling, and cost resulted in the procurement of a hard red (coarse grain) granite block of about 23 x 74 x 94 cm. This granite block has smooth as well as rock-pitch finish rough surfaces. The average peak-to-valley roughness of the rock surface is about 2 cm.

6.2 FABRICATION OF TRANSMITTING AND RECEIVING TRANSDUCERS

In view of the theoretical discussions presented earlier (see 5.1) PZT-4 and LMN piezoelectric materials appear to be best suited for transmitting transducers. No vendor could be found who could provide us with the desired shape and size of LMN. Hence, only PZT-4 piezoelectric material was selected for the design and fabrication of transmitting transducers. Because of the earlier discussed advantages of multiple-layer over single-layer transducers, Longevin-type half-wavelength-thick sandwich transducers (using PZT-4 material annular discs) were designed and constructed. A typical design is given in Figure A-2. For reasons of higher directivity, narrower beam, purity of the generated wave type, transducers having large value of D/λ (i.e., $D/\lambda \gg 1$) should be used. However, for reasons such as cost, availability, and simplicity, five transducers having D/λ less than unity were designed and constructed. All these transducers resonate (in their thickness mode) in the vicinity of 33 kHz. The first three transducers are cylindrical in shape having a D/λ of about 2/7. The fourth one is the same as the first three, but the front plate was tapered out so that it gave a D/λ of about 4/7. This is referred to as a conical sandwich. The fifth transducer is identical to the first three except that it has a D/λ of about 5/7. A photograph of this transducer is shown in Figure 6-1.

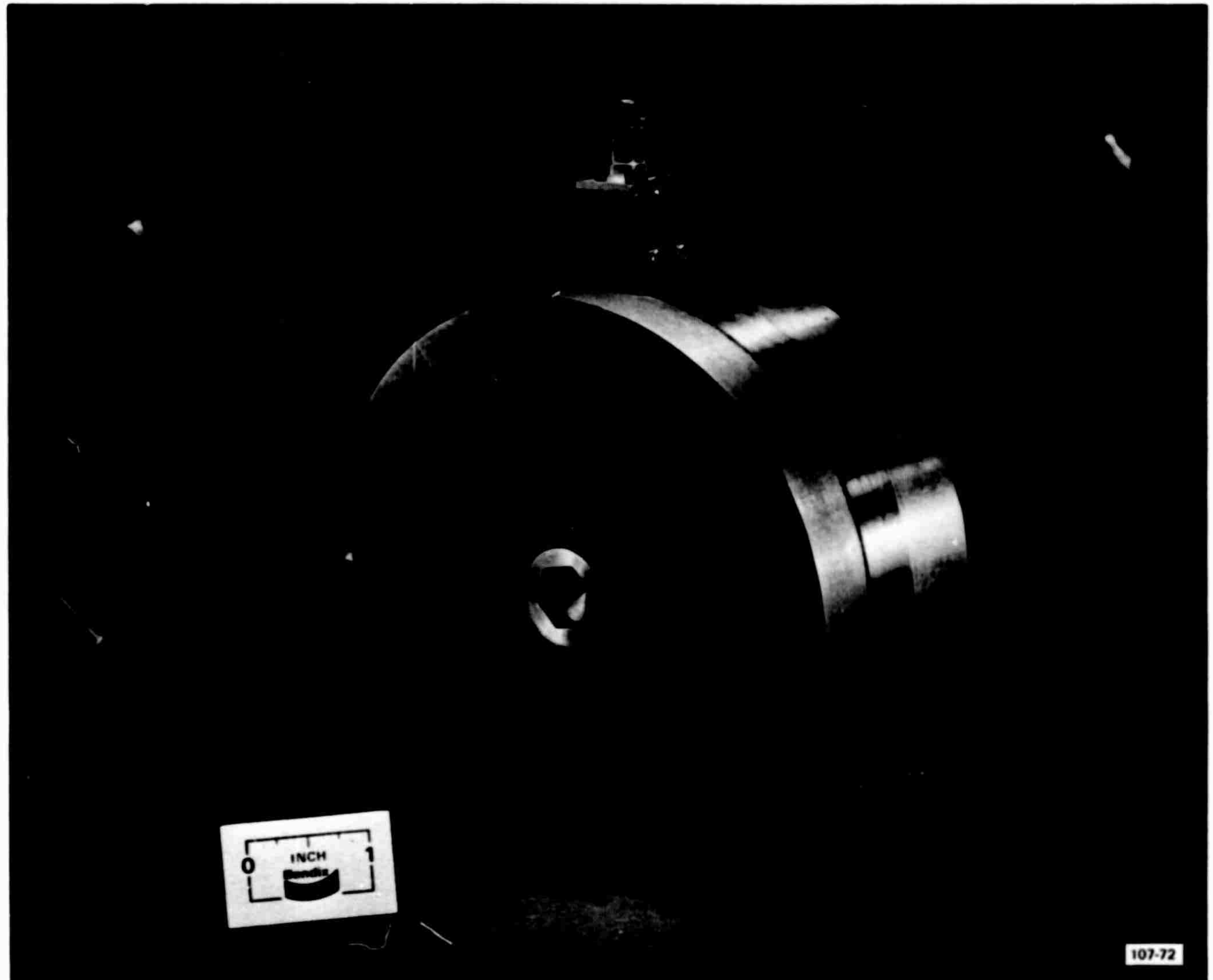


Figure 6-1 - Cylindrical Sandwich Transducer 5 Inches in Diameter

PZT-4 and PZT-5 piezoelectric materials were found to be well suited as receiver materials. Hence, resonant sandwich transducers constructed for transmitting purposes are equally well suited as resonant receivers. Resonant receivers are expected to have higher signal-to-noise ratios than non-resonant receivers; however, non-resonant receivers provide better resolving capabilities than the resonant ones because of their broad band frequency performance. Thus, several non-resonant (planar discs) receivers have also been constructed from LMN piezoelectric material to evaluate their performance relative to PZT material.

6.3 EXPERIMENTAL SETUP

A typical block diagram of a pulse-reflection and transmission setup was shown in Figure 4-1. Various types of electrical excitation were used. These were:

(1) Narrow (several microseconds duration) high-voltage impulses (up to 1600 V peak open-circuit voltage) generated by a James Electronic Impulse Generator. This generator has a high source impedance and therefore provided persistent electrical ringing across the transducer which yielded a rather long duration acoustic pulse. Figures 6-2 and 6-3 show the electrical voltage (including ringing) across the transducer and the detected acoustic signal transmitted through 74 cm of rock specimen.

(2) PM-CW signal was obtained by gating the signal from a General Radio Audio frequency generator. The output of the gate was amplified by a Dynakit Mark III before being applied to the transducer. Again, in this case, persistent electrical ringing was observed across the transducer which resulted in very long duration acoustic pulses.

(3) PM-CW signal obtained directly from a Tone Burst Generator which has a low output impedance of 50Ω. Relative to the first two setups, very little electrical ringing was observed (as shown in Figure 6-4) across the transducer. This is due to the fact that in the absence of an electrical signal, this generator appears as a short circuit to the transmitter and thus increases the damping of the electrical signal. In this case, the pulse-width of a radiated acoustic signal would be relatively independent of electrical excitation and therefore would be relatively short as compared to the first two excitation schemes. The tone-burst generator used in this setup is made by Interstate Electronic Corporation (Model F34). The only problem with this generator is that a maximum of 10 V peak across 50Ω impedance can be obtained, which is inadequate for our application. Thus, efforts are currently being made to procure, or design, a high-voltage low-output-impedance amplifier.

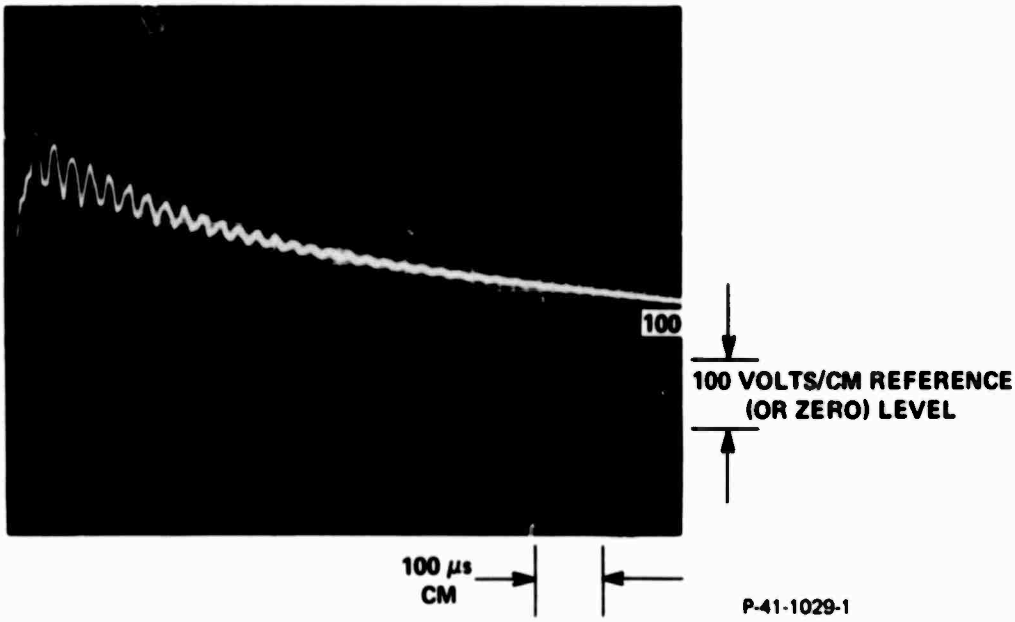


Figure 6-2 - Typical Impulse Generator Excitation of 2-Inch Cylindrical Sandwich Transducer

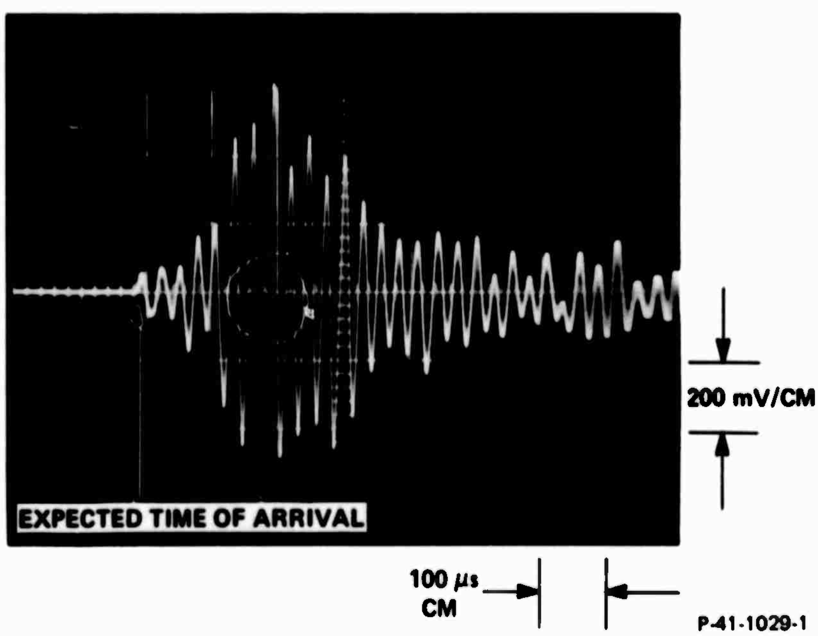
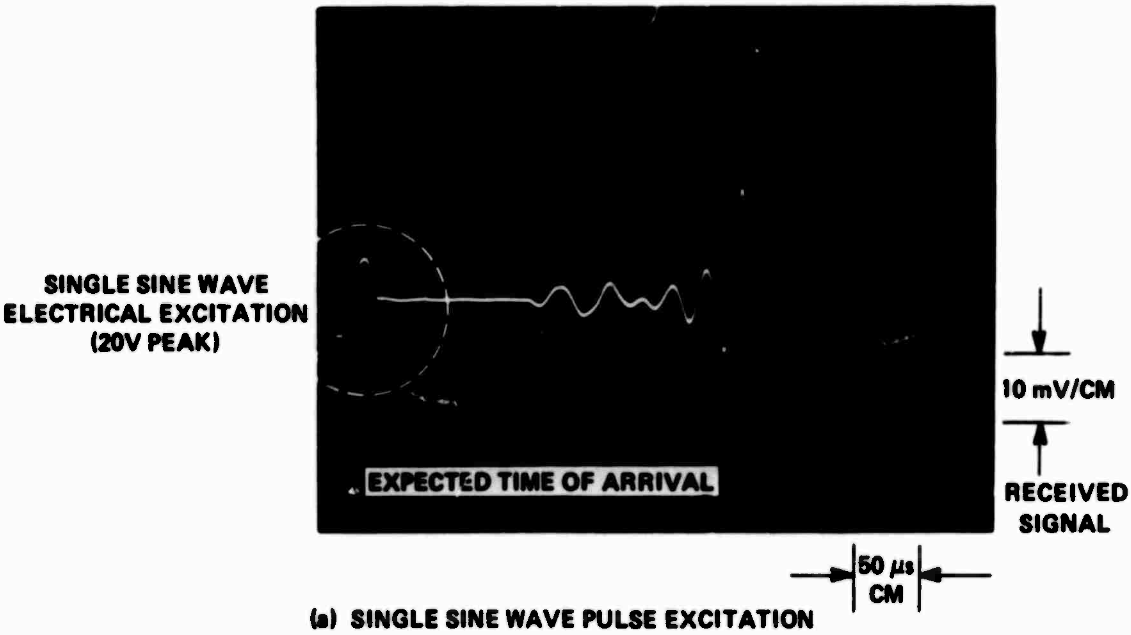
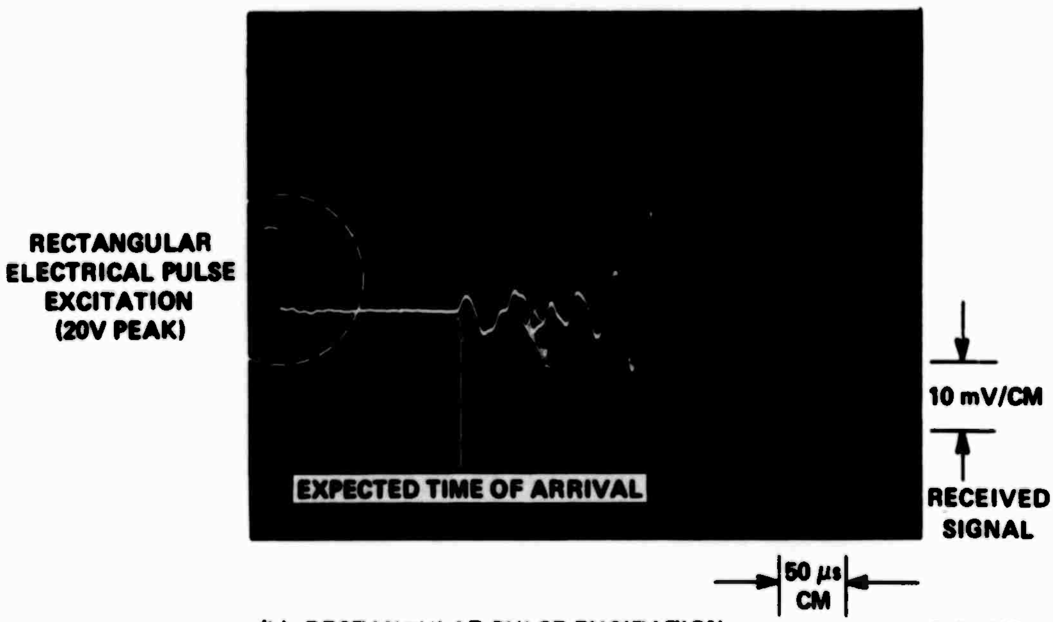


Figure 6-3 - Typical Signal Transmitted Through 74 cm Granite (The incident signal is generated by the above electrical excitation across a 2-inch cylindrical sandwich transducer)



(a) SINGLE SINE WAVE PULSE EXCITATION



(b) RECTANGULAR PULSE EXCITATION

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Figure 6-4 - Typical Signal Transmitted Through 74 cm Granite
(The electrical signals are generated by a tone-burst generator)

6.4 SPURIOUS SIGNALS

In this experimental study, only the leading edge of a signal transmitted through a medium could be clearly identified. In the case of a reflected signal, even the leading edge cannot be unambiguously identified. Some of the probable causes of spurious signals are: (1) reverberations in test material, (2) interference from the surface of the material under test, and (3) interference caused by mode-conversion.

6.4.1 Interference from the Surface

When separate probes are used for transmitting and receiving, the sound pulse can be directly transmitted to the receiver along the surface of the material in the form of longitudinal, shear, and Rayleigh waves. These waves arrive at the receiver at different times due to their different sound velocities. The amplitude of the surface waves has been reported to be higher than that of the body waves, which makes this interference more significant particularly in lossy rocks. Surface waves reflected from the edges of a test material can also cause additional disturbances.

6.4.2 Interference Caused by Mode-Conversion

When an ultrasonic beam meets a reflecting surface, mode conversion can occur when the beam is not at right angles to the reflecting surface. This is the most common problem encountered in any laboratory. An example of mode-conversion is illustrated in Figure 6-5 for a rectangular block similar to the test specimen.

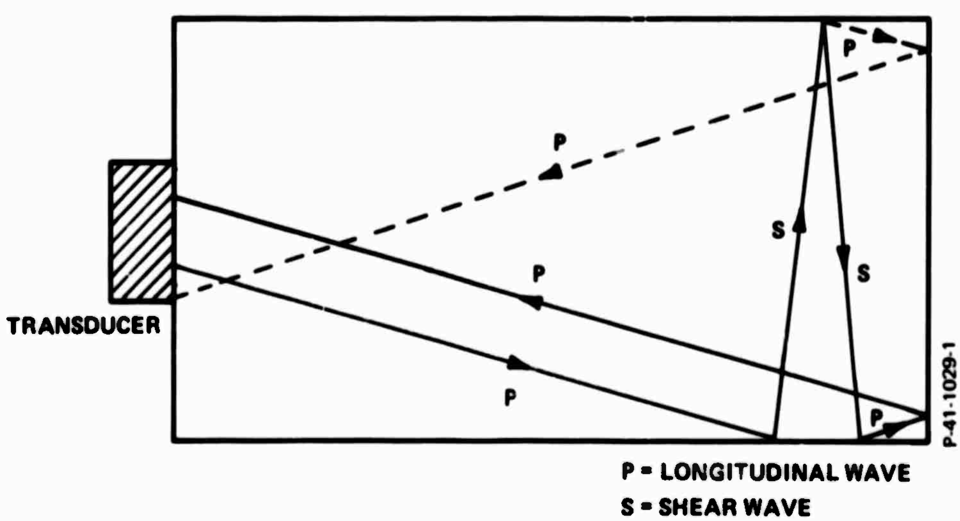

Figure 6-5 - Spurious Signals Due to Mode-Conversion in a Finite Size Specimen

Since in our application the actual propagation medium of interest is semi-infinite in extent, we do not expect much interference from the mode-conversion phenomena. However, in our laboratory set-up, we are plagued by this interference because of the finite size and low-loss characteristics of our test rock specimen.

6.5 MEASUREMENT OF SOUND VELOCITY AND ATTENUATION

The velocity of longitudinal waves in the test rock specimen was measured to be 5 km/sec by measuring the transit time of a signal in a transmission test. The experimental setup for transmission is the same as that for reflection except that the receiver is placed on the surface opposite to the one on which the transmitter is located (see Figure 4-1). The attenuation coefficient of rock could not be measured because multiple echos could not be identified in the presence of spurious signals.

6.6 COUPLING STUDIES

Consistent with the theoretical discussions presented in Section 5.2, we had selected (1) water (mixed with a wetting agent), (2) glycerine, (3) silicone, (4) greased neoprene, (5) J. E. Coupling paste (supplied by James Electronics, Inc.), and (6) Dow Corning's Sylgard 51 gel as couplant candidates for experimental evaluation. These couplants were experimentally evaluated by carrying out transmission tests through the 75 cm thickness of the rock specimen. The experimental setup is shown in Figure 4-1. Transmission tests were conducted at about 33 kHz by coupling energy through smooth as well as rough rock surfaces. At the test frequency, the average roughness of the test specimen was about 3/8 of the signal wavelength. These couplants were evaluated as a function of their thickness, which in most cases was gradually increased up to a wavelength in the coupling medium.

Despite the fact that steady-state (relative to the duration of transmitted wave train) conditions existed for the behavior of couplants, only the transient response of a couplant (i.e., the first cycle of the leading edge of the signal transmitted through a couplant) could be clearly identified, due to the presence of spurious signals. Figures 6-6 and 6-7 show the transmitted signal through 74 cm of the test rock specimen using resonant transmitting and receiving transducers. In these tests, a James Electronics impulse generator was used to excite the resonant transmitter.

The experimental results indicate that under transient response:

(1) The transmission characteristics of a couplant are relatively independent of the thickness of the couplant as would be expected from theoretical considerations.

(2) The relative amplitude of the signal transmitted through various couplants is not the same as that expected from theoretical considerations. For example, based on theory, the relative amplitude of the signal transmitted through

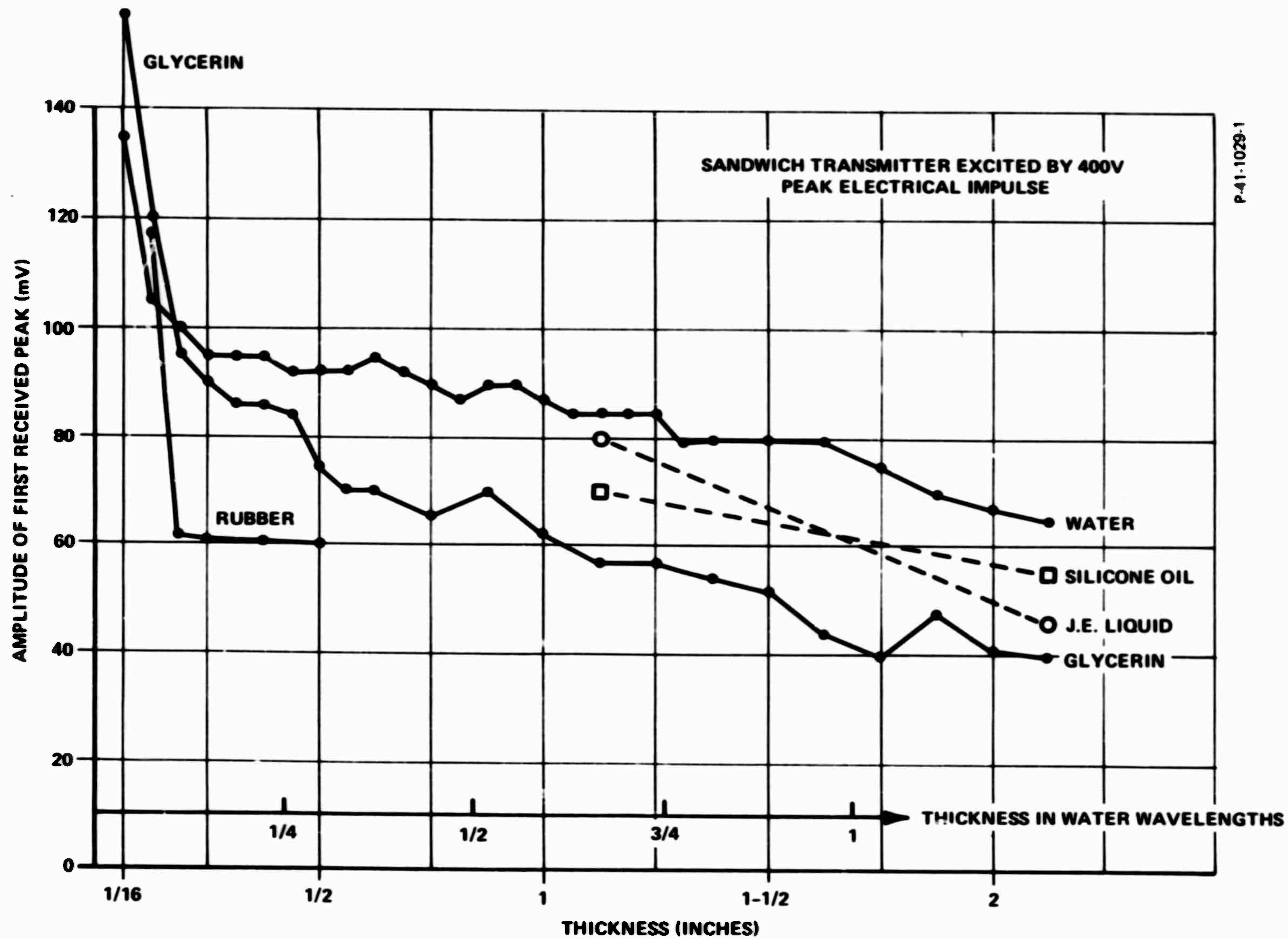

Figure 6-6 - Relative Transmission of Various Coupling Materials Through 74-cm Red Granite Having Smooth Surface

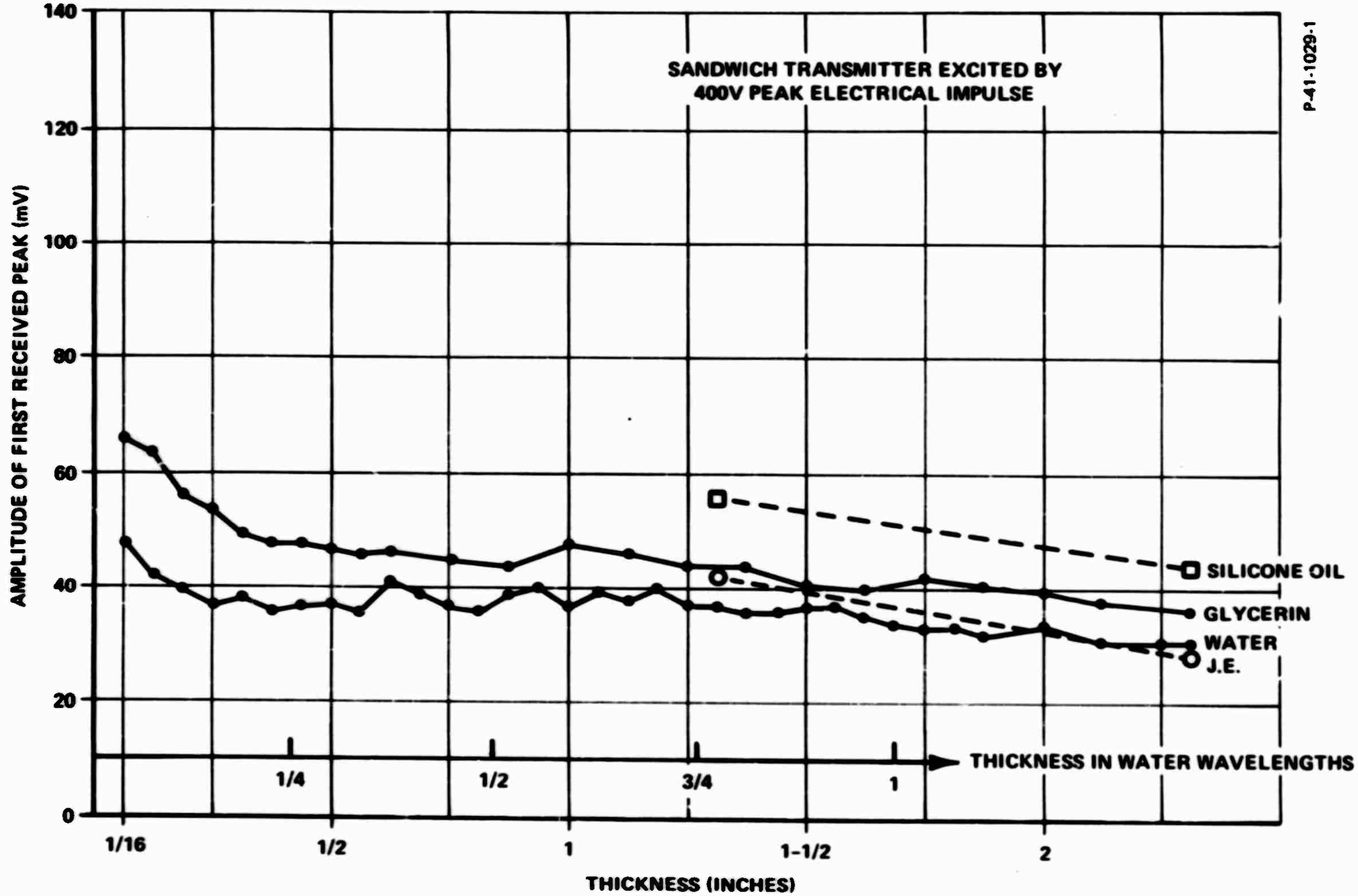

Figure 6-7 - Relative Transmission of Various Coupling Materials Through 74-cm Red Granite Having Rough Surface

water should be twice as large as that transmitted through silicone oil, and one and one-half times that transmitted through glycerine. However, experimental results do not agree with these theoretical predictions. The probable causes for this disagreement may be (a) trapped air-bubbles, (b) surface wetting, and (c) adhering properties of a couplant.

(3) Coupling efficiency is usually somewhat higher when energy is coupled to smooth rather than to rough surface rock.

(4) Water, glycerine, and silicone oil coupled equally well.

Practical considerations such as cost and electrical hazards lead us to suggest the use of glycerine as a contained couplant. However, in applications where a rock surface is very rough and the contacting couplant fails to provide adequate acoustic contact, a noncontacting method of coupling may be used. This could be accomplished by maintaining a water jet (mixed with a wetting agent) between the transducer and the rock surface.

6.7 REFLECTION TESTS

Due to the presence of spurious signal (discussed earlier), reflected signal could not be unambiguously identified in the signal received by a detector located on the same surface as the transmitter. In the field test, the interference from spurious signals is expected to be minimum due to the semi-infinite extent of propagation medium. However, these reflected signals could be identified when high frequency signals ($\sim$250 kHz) were incident on a coal specimen.

SECTION 7

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APPENDIX A

BASIC PRINCIPLES

Some of the basic principles that are needed in the design and development of transducers are briefly described in this section.

Transducer Theory

The magnitude and character of the piezoelectric effect in any piezoelectric material greatly depends upon the orientation of applied electric field or force with respect to the axes of the material. In applications similar to one under consideration, a commonly used transducer is the one vibrating in its thickness mode with electrodes attached to the plane faces. Other possible modes of vibration are radial and circumferential. In our application, longitudinal waves would be generated (or received) by a transducer operating in its thickness mode. This is due to the fact that thickness mode, as compared to radial or circumferential mode, has higher electro-acoustic efficiency and smallest angular divergence of the radiated beam.

A transducer can be designed as a resonant device operating at or around one of its mechanical resonant frequencies, or as a non-resonant device operating over a large frequency range well below its lowest resonant frequency.

Resonant Transducer Transmitter Design

Depending upon the loading conditions on both sides of the transducer material, the transducer can be designed to resonate when its thickness is one-quarter, or one-half of the signal wavelength. For a transducer disc of acoustic impedance Z_0 located in between two materials 1 and 2 with impedances Z_1 and Z_2 (as shown in Figure A-1), the transducer would oscillate in $\lambda/4$ resonance if media impedances are such that either (a) $Z_1 > Z_0 > Z_2$; or (b) $Z_1 < Z_0 < Z_2$. This transducer would oscillate in $\lambda/2$ resonance if media impedances are such that (a) $Z_1 > Z_0$ and $Z_2 > Z_0$; or (b) $Z_1 < Z_0$ and $Z_2 < Z_0$. In practice, it is easy to design a transducer to oscillate in $\lambda/2$ resonance since one side of the transducer can be easily terminated into a lower-impedance medium (for example, air), and the other side radiating into a medium (for example, a rock) whose impedance is smaller than that of the transducer material.

The mechanical quality factor Q_m of a half-wavelength-thick transducer is given by

$$Q_m = \frac{\pi}{\ell n \delta} \qquad \text{(A-1)}$$

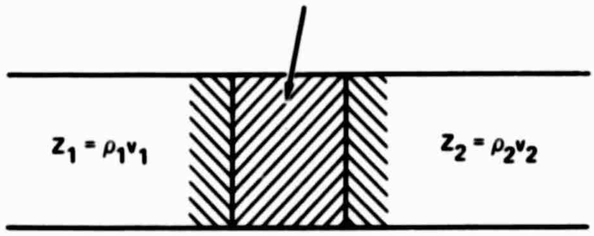

Figure A-1 - Transducer Between Two Radiating Media

where the damping coefficient δ is given by

$$\delta = \frac{(Z_0 + Z_1)\ (Z_0 + Z_2)}{(Z_0 - Z_1)\ (Z_0 - Z_2)} \qquad \text{(A-2)}$$

Air-Backed Half-Wavelength Thick Transmitter

In this case (see Figure A-1),it is assumed that air is backing the transducer on one side ($Z_2 \approx 0$) while the other side of the transducer is radiating into a rock medium, such that $Z_0 < Z_1$. The transducer is assumed to be made of material having a density ρ_m, and particle velocity v_m. Basic relationships between electrical and mechanical quantities of this transducer, resonating at a frequency f, are summarized in Table A-1. At very high frequencies (i.e., 2 ka >> 1), the radiation impedance Z_r reduces to ρvA, since R_1 (2 ka) approaches unity while X_1 (2 ka) approaches zero.

The static capacitance C_o of the piezoelectric material is generally undesirable since it shunts the electrical source or the driving amplifier, and therefore the source has to supply extra current. This capacitance C_o can be cancelled by inserting an inductance coil in series or parallel to the electrical input terminals of the transducer. Optimum power conversion occurs when the source internal impedance is equal to the input impedance of the transducer at resonance, after C_o has been tuned out. However, if the maximum power is to be radiated by the transmitter irrespective of its conversion efficiency, the matching requirements may differ from the one given for optimum conversion efficiency.

The frequency characteristics of a resonant transducer are determined by the combined effect of mechanical quality factor Q_m and the electrical quality factor Q_e of the transducer. These quality factors are given by

Table A-1 - Properties of a Half-Wavelength Thick Air-Backed Resonant Transmitting Transducer

Quantity	Symbol	Unit	Expression
Total Radiating Area	A	meter^2 (m^2)	πa^2
Static Capacitance	C_o	Farads/m	$\varepsilon_r \varepsilon_o A/\ell$
Transformation Factor	ϕ	Coulomb/m	eA/ℓ
Total Radiation Impedance*	Z_R	kg/sec	$vA [R_1 (2 ka) + X_1 (2 ka)]$
Particle Velocity at Transducer Face	u	m/sec	$2 \phi V/A$
Sound Pressure at Transducer Face	p	Newton/m^2	$2 \phi v/A$
Total Acoustic Power Radiate	W	Watts	$4 \phi^2 V^2/Z_r$
Motional Current	i_m	Amps	$2 \phi u$
Displacement Current	i_o	Amps	$2\pi f C_o V$
Motional Resistance	R_e	Ohms	$\rho vA [R_1 (2 ka)]$
Motional Reactance	X_e	Ohms	$\rho vA [X_1 (2 ka)]$

*R_1 (2 ka) and X_1 (2 ka) are mathematical functions (where $k = 2\pi/\lambda$) which can be found in any acoustic text book.[17]

$$Q_m = \frac{\pi}{\ell n \dfrac{Z_0 + Z_1}{Z_0 - Z_1}} \simeq \frac{\pi}{2} \frac{\rho_m v_m}{\rho v}$$

$$Q_e = \frac{\pi}{4k_c^2} \frac{\rho v}{\rho_m v_m} \tag{A-3}$$

where k_c^2 is the electromechanical coupling coefficient defined in equation (4b). From the above equations we see that with increasing loading impedance (ρ v) Q_e increases while Q_m decreases.

In a pulse-reflection technique, usually a short transient response of a loaded transducer is desired which requires low values of both Q_m and Q_e. Q_m can be lowered by either increasing the loading impedance (but still less than transducer impedance), and/or replacing the air-backing of the transducer by a lossier acoustic medium whose impedance can also be altered, if necessary, by inserting a quarter-wavelength transformer between the transducer and the loading medium. The replacement of air-backing usually requires lossy backing material many wavelengths long which may not always be practical at low ultrasonic frequencies. Low Q_e will ensure the least possible change in relative amplitude and phase of the pulse throughout its frequency spectrum. Lower values of Q_e can be achieved without altering Q_m by shunting the transducer by a resistance R_o, after the static capacitance C_o has been tuned out. In this case, the modified electrical quality factor Q_e' becomes

$$Q_e' = \frac{Q_e}{\left(1 + \frac{Q_e}{\omega C_o R_o}\right)} \qquad \text{(A-4)}$$

Receiving Transducer Design

Depending upon the application, a receiver can be designed to operate as either a non-resonant or a resonant device. The dynamic sensitivity of an open circuit non-resonant receiver (well below its resonance) is given by

$$\frac{\text{Voltage}}{\text{Force}} = \frac{V}{F} = \frac{1}{\phi}\left(\frac{k_c^2}{1 + k_c^2}\right) \qquad \text{(A-5)}$$

In practice, the voltage output of a non-resonant receiver is less than the open-circuit voltage due to the loading of connecting cables. This loss in sensitivity can be minimized by using a piezoelectric material with a higher dielectric constant.

The usage of a resonant receiver increases the detection sensitivity at the expense of frequency response. The highest output is obtained if the operation takes place both at mechanical and at electric resonances. The former requires that it is a half-wavelength thick at the receiving frequency. The latter requires the tuning out of the capacitance of crystal and the cable. The pressure sensitivity of a loaded resonant receiver is found to be

$$\frac{\text{Voltage}}{\text{Pressure}} = \frac{V}{\rho} = \frac{4A}{Z_R\ G} \qquad \text{(A-6)}$$

where Z_R = Radiation impedance, A is the receiving area; and

$$G = \frac{1}{R_{load}} + \frac{4\phi\ 2}{Z_R}$$

The voltage across a lossless resonant receiver which is matched for optimum power transfer (i.e., $R_L = Z_r/4\alpha^2$) is half that of the open-circuit voltage across receiver.

Both frictional and scattering loss mechanisms in a rock propagation medium preferentially attenuate the high frequency components of a pulse. In the case of highly attenuating rock medium, the pulse shape is continuously changing as it propagates through the medium. The end result is that the pulse experiences a gradual shift of the frequency content of the low end of the spectrum. Hence, if a resonant transducer is used to detect the received signal, the resonant frequency of the receiving transducer should be a little lower than the center frequency of the incident pulse.

Multiple-Layer Piezoelectric Transducers

At ultrasonic frequencies of interest (below 100 kHz), a multiple-layer transducer may be easier to fabricate than a single slab transducer. A composite piezoelectric transducer is made up of a piezoelectric element attached to one or two materials which are not piezoelectric. A common type of multiple-layer transducer is the Longevin sandwich-type of structure (shown in Figure A-2) which consists of an aluminum and a steel block cemented to a piezoelectric crystal. The advantages of the multiple-layer transducer are that (1) less piezoelectric material is needed and the cost is less, (2) a lower voltage is required for the same electric field strength, and (3) it is relatively simple to construct.

Directivity Effects of a Transducer

A sound beam radiated by a uniformly excited circular piston (a typical sound radiator) behaves as follows:

(1) The character of the acoustic beam is determined by the ratio of diameter D to wavelength λ of the radiator. If this value is large, a well collimated beam is obtained in the near field. In the far-field region, beginning at $D^2/4\lambda$, beam lobe is confined between the angles $\pm \sin^{-1} (1.2\ \lambda/D)$.